

A CENTRIFUGE CO₂ PELLET CLEANING SYSTEM

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ABSTRACT

An advanced turbine/CO₂ pellet accelerator is being evaluated as a depaint technology at Oak Ridge National Laboratory (ORNL). The program, sponsored by Warner Robins Air Logistics Center (ALC), Robins Air Force Base, Georgia, has developed a robot-compatible apparatus that efficiently accelerates pellets of dry ice with a high-speed rotating wheel. In comparison to the more conventional compressed air 'sandblast' pellet accelerators, the turbine system can achieve higher pellet speeds, has precise speed control, and is more than ten times as efficient. A preliminary study of the apparatus as a depaint technology has been undertaken. Depaint rates of military epoxy/urethane paint systems on 2024 and 7075 aluminum panels as a function of pellet speed and throughput have been measured. In addition, methods of enhancing the strip rate by combining infra-red heat lamps with pellet blasting and by combining the use of environmentally benign solvents with the pellet blasting have also been studied. The design and operation of the apparatus will be discussed along with data obtained from the depaint studies.

INTRODUCTION

The centrifuge CO₂ cleaning system is a method of cleaning surfaces. Use of CO₂ is environmentally sound because it is readily available as a by-product stream from many industrial processes. The cleaning action takes place when the high-speed pellet of frozen CO₂ impacts the surface and knocks loose any contamination. Depending on the speed of the pellets, the cleaning action can be adjusted from a low impact pressure regime up to an aggressive impact during which relatively hard surfaces can be removed or etched. The cleaning applications of the centrifuge-based pellet accelerator are similar to those of commercially available CO₂ pellet cryoblasting systems that use compressed air to accelerate the pellets. The distinguishing feature of the centrifuge system is that it can achieve much higher pellet speeds at increased efficiency, which allows the centrifuge system to perform more aggressive cleaning and etching tasks. For example, removing epoxy-based paints from aircraft, a task that previously used large quantities of methylene chloride solvents, may be economically feasible with high-speed CO₂ pellets. Another application is the cleaning of surfaces contaminated with toxic, hazardous, or radioactive substances. In these applications the lack of a secondary contaminated waste stream is of great benefit.

THEORY OF OPERATION

The centrifuge accelerates cryogenic pellets with virtually no contact forces between the pellet and the accelerator. The acceleration process utilizes the commonly known property that frozen CO₂ (dry ice) 'floats' on a self-generated gas bearing when placed on a smooth surface. Pellets injected into a high-speed rotating track are thus accelerated with negligible friction loss, Fig. 1. Figure 2 shows the typical geometry of a track in a centrifuge wheel. Pellets exiting the wheel have a speed v_p determined by the peripheral speed of the wheel v_w and the exit angle θ between the track and the tangent of the wheel, Fig. 2.

$$v_p = 2v_w \cos(\theta/2) \quad (1)$$

The track geometry for our present wheel has an exit peripheral angle of 45 degrees giving a pellet speed of 1.75 times the wheel tip velocity. Speeds of up to 350 m/s (1150 ft/s) and acceleration efficiencies of 80% (65% overall efficiency) have been achieved. All pellets accelerated by the wheel have essentially the same velocity which means that the entire stream can be delivered to the surface at the optimal velocity for the particular application. This is in contrast to compressed air systems which deliver pellets with a range of velocities.

The interaction of the high-speed pellet with a surface can be modeled using the same physics as the impact of a high speed fluid droplet on a surface, Fig. 3. In this case the impact pressure created on the surface is given by the 'water hammer' equation. This equation relates the impact stress s to the pellet velocity v_p , pellet density ρ_1 and compressive sound speed U_1 :

$$s = \rho_1 U_1 v_p \quad (2)$$

for impact with rigid surfaces and

$$s = v_p \rho_1 U_1 \rho_2 U_2 / (\rho_1 U_1 + \rho_2 U_2) \quad (3)$$

or impact with semirigid surfaces. The compressive sound speed is one measure of the pellet's hardness. Even though dry ice is relatively soft, at high speeds the pressures developed during impact can be made larger than the yield strength of most materials. Depending on the surface being impacted, there is a characteristic threshold velocity above which erosion takes place. It is interesting to note that this physics model corresponds to any abrasive media which is significantly softer than the surface being impacted. Therefore, all of the soft abrasive and liquid impact cleaning technologies are basically the same. That is, one would expect to achieve comparable results with high pressure water, CO₂, or plastic media abrasives for comparable surface impact pressures as given by Equations 2 and 3.

The differentiating features of the soft abrasive technologies depend on the speed and efficiency of the acceleration technology, the cost of the

equipment, the cost of the abrasive material, and the cost of the recovery or cost of disposal of the abrasive material. The principle advantage of the centrifuge CO₂ system is that it can achieve pellet speeds high enough to perform aggressive etching. Furthermore, it is efficient and the waste processing is done with a simple high efficiency air filtering system. Another distinguishing feature of the CO₂ system is that during impact the CO₂ is converted from a solid to a high-pressure supercritical fluid which undergoes a rapid decompression and expansion which can be quite effective in dissolving hydrocarbons and in sweeping away surface deposits. These effects are especially important in cleaning porous surfaces.

EXPERIMENT

The experiment involved design, fabrication, and testing of a robot compatible device, similar to Fig. 1. The hardware used to accelerate the CO₂ pellets consists of a high-speed electric motor and a specially designed aluminum accelerator disk. This unit uses a lightweight 11-kW (15-HP) brushless DC motor with a 0.35-m (14-in) wheel. The weight of the accelerator is kept low for compatibility with the robot. This unit will accelerate CO₂ pellets delivering up to 454 kg/h (1000 lbs/h) at velocities of 350 m/s (1150 ft/s) and clean a swath about 13-cm (5-in) wide as it is scanned across a surface. A commercial CO₂ micropellet fabrication machine was used to feed the centrifuge. The unit was mounted on a GMFanuc S-420F robot, which was programmed to move the device across sheets of painted aluminum panels at various rates in order to obtain depainting rates.

Painted panel samples which measured 0.51 m by 1.02 m (2 ft by 4 ft) were mounted on a horizontal support matrix which was designed to simulate the rib structure of the aircraft. This was mounted on a table top and surrounded by an exhaust shroud to collect the carbon dioxide gas and paint chips. A 57-m³/min (2000 CFM) HEPA filter system collected this gas and directed the exhaust outside the building. The pelletizer was started about 45 minutes prior to the run to collect a supply of pellets for the run. The robot was programmed to sweep the device in a linear scan at programmable rates for designated distances across the panel. Parameters such as offset distance and starting position were also programmable. The robot scan was generally tested prior to operating the device. If preheating lamps were used during the run, they would be turned on first. The motor speed would then be set and the motor turned on. Pellet feed would then be initiated and the robot scan would be initiated.

Four different aluminum substrates used in this work: 2024-T3 and 7075-T6 aluminum each with a thickness of 0.081 mm (0.032 in) and 1.57 mm (0.062 in). The panels were cut, marked, and sent to Warner Robins ALC for painting. They received a coat of MIL-P-23377 epoxy-polyamide primer on both sides and a finish coat of gray gloss MIL-C-83286 urethane-aliphatic isocyanate paint on the side to be tested. The samples were then artificially aged and returned to ORNL. There were a total of twenty test panels prepared. Samples were run at room temperature with various pellet feed rates and scan rates, at elevated temperatures, and with solvent augmentation. Cleaned areas

were measured using the 'paper dolly' method in which the cleaned area was traced on paper, cut out, and weighed. Weights were then compared to weights of known areas to determine the area cleaned. The results of these tests are presented below.

RESULTS AND DISCUSSION

PELLET VELOCITY MEASUREMENTS

Double pulse strobe lighting with 200 μ s between pulses was used to determine pellet velocities. Distances between double-exposure video images of the same pellet were used to calculate distance traveled during this time period. Results of analysis of about 200 individual pellet trajectories from 24 video frames are shown in Fig. 4. The theoretical speed at the point of release on the wheel at this velocity (12,000 rpm) is 390 m/s (1280 ft/s). Theoretical calculation of velocity reduction due to air drag for several sizes of spherical pellets are presented as the lines in the figure. Pellets are fed into the wheel as 1-mm diameter cylinders and it is plausible that they may undergo breakage in the feed line and during acceleration. Video images of the pellets were not of good enough quality to measure actual pellet diameter. Pellets strike the surface being cleaned in the range of 18 to 25 mm (7 to 10 in) from the wheel. In this range, pellets are traveling at a speed of about 350 m/s (1150 ft/s).

STRAIGHT BLASTING RESULTS

During a typical scan, the robot was programmed to clean ten 120-mm (4.72-in) long segments at rates of 64, 32, 28, 16, 12, 8, 6, 4, and 3 mm/s (12.6, 6.3, 5.5, 3.1, 2.4, 1.6, 1.2, 0.8, and 0.6 ft/min). Figure 5 shows the fraction of the surface cleaned as a function of the quantity of pellets striking the surface for three different pellet velocities. The curves have a sigmoid shape showing an incubation period where little or no erosion occurs, followed by period of rapidly increasing erosion rate and finally leveling off as 100% cleaning is approached. The device cleans a 13.3-cm (5.25-in) swath with the cleaning efficiency being the highest at the center. At optimal strip rates, the center of the swath is fully cleaned with the edges left partially stripped. A 2.5-cm (1-in) overlay on the next pass completes the stripping of the edge region. Figure 6 shows the effect of pellet feed rate on cleaning rate at the highest pellet speed (1150 ft/s). This curve again shows behavior typical of most erosion processes in that there is some incubation period below which cleaning does not occur, followed by a segment of rapidly increasing cleaning rates. At higher rates the data is showing signs of leveling off. It appears that at 12,000 rpm at least 79 kg/h (175 lbs/h) is the incubation rate and that about 227 kg/h (500 lbs/h) may be the optimal operating point where depaint rates of about 6.7 m²/h (1.2 ft²/min) are achieved.

Figure 7 shows results of Almen strip test runs. Almen test strips were cut from 0.81-mm (0.32-in) thick 2024T3 painted panels and run under typical cleaning conditions. The curves show incubation periods similar to those for cleaning curves shown in Fig. 5. Almen deflection and fractional cleaning also appear to be related, and it appears that the Almen deflection associated with a specific level of cleaning may be independent of the pellet speed. Two

important effects must be considered in evaluation the potential surface hardening, which would result from multiple depaint cycles. First, the Almen deflection curves tend to saturate with additional dosing so that each subsequent cleaning would produce less additional Almen deflection than the previous cycle. Second, the paint actually protects the surface, especially through the incubation period, so that curves for Almen deflection for the accumulated dose for unpainted material will be higher than those for painted specimens.

HEAT AUGMENTED DEPAINTING

In an earlier phase of this program, it was found that mild heating of the surface made dramatic increases in depainting rate; therefore, further tests in this area were performed with this new accelerator. Three heating methods were explored: a 5-kW hot-air gun blowing on the surface just ahead of the blast area in the scan direction, two 1.2-kW Research, Inc., infrared lamps mounted on the unit in the scan direction, and portable Wal-Mart heat lamps used to warm the surface prior to scanning. The temperature of the surface was read just ahead of the blast zone with an Exergen infrared thermometer and recorded. Results show that the important factor in determining depaint rate is the surface temperature and not the method used to produce the temperature increase.

Figure 8 shows the results of experiments to augment the strip rate by heating the paint surface. The quartz infra-red heat lamps, mounted on the turbine wheel housing, preheat the surface to a temperature around the boiling point of water (212° F) for a few seconds preceding the blasting. The heating softens the paint and thereby increases the depaint rate by a factor of 3-to-4 times the unheated strip rate.

SOLVENT AUGMENTED DEPAINTING

Another option available to enhance strip rate is the use of environmentally benign solvents to presoften the paint. There are many such solvents available, but only two were used to test the concept: methyl-ethyl-ketone (MEK) and 3M Safest Strip. MEK is very volatile and would evaporate too rapidly to have any effect if just painted on the surface. This problem was circumvented by laying a towel on the surface, soaking it with MEK, and covering with plastic to prevent evaporation. Safest Strip contains agents that retard evaporation; however, the surface was also covered after application to prevent hardening. With these mild solvents the surface must be soaked for some time to cause an effect. In these tests the solvents were left on the panel over the weekend, or about three days. These samples were run at only one scan rate (9.5 ft/min), and the results are shown in Fig. 9 with results from heating and straight blasting for comparison. As can be seen in the figure, solvent augmented cleaning rates are on the order of four times the unaugmented rates.

ADDITIONAL TESTING

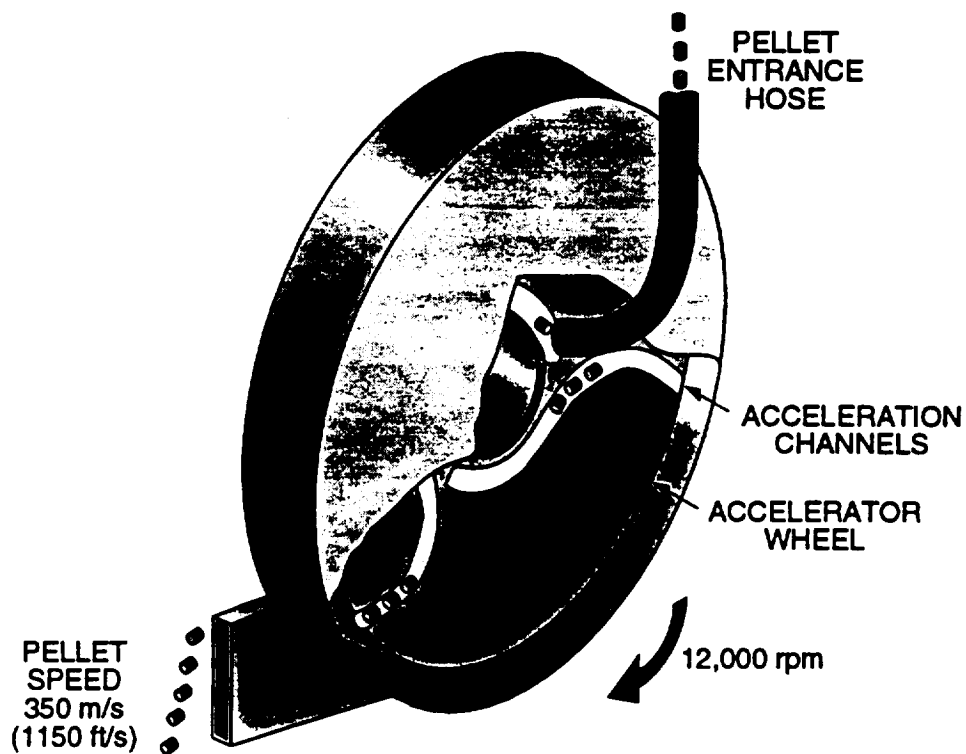
In addition to the paint stripping program, a limited amount of testing with the centrifuge/CO₂ blaster was also performed to characterize its cleaning capabilities on a variety of surfaces. Several objects typical of those found in a decontamination project were cleaned. These included: a painted concrete block, greasy gear assembly, a concrete floor sample, enamel coated steel siding, some limestone rocks, a wooden pallet, and a rusty angle iron. Also, through a DOE-sponsored program designed to assist U.S. industry, a number of private companies ran short tests with their own samples to determine the potential of implementing CO₂ blasting in their specific industrial process.

CONCLUSIONS AND RECOMMENDATIONS

This program has produced a robot compatible centrifugal dry ice pellet depainting device for Warner Robins ALC. This device is about ten times the efficiency of conventional dry ice blasting equipment, which utilizes pneumatic acceleration. The device has been shown to be capable of delivering 454 kg/h (1000 lbs/h) at velocities of 350 m/s (1150 ft/s). The device is powered by a specially developed light-weight brushless DC motor which develops over 15 kW (20 HP) at 12,000 rpm. While the device has not been qualified for operation at higher velocities, the motor has been run at 16,000 rpm; the entire device has been tested to 14,000 rpm without pellets. Modest increases in velocity may be desirable to increase cleaning rates. The device was mounted on a robot at ORNL, which scanned it across sample surfaces. It was shown to clean a swath about 13.3-cm (5.25-in) wide with a 3.8-cm (1.5-in) standoff distance. Depainting rates in excess of 5.6 m²/h (1-ft²/min) were measured with a pellet feed rate of 227 kg/h (500 lbs/h). Rates in excess of 22 m²/h (4 ft²/min) were measured when the paint was preheated to temperatures on the order of 100 C (212 F) or when the paint was presoftened with several environmentally benign paint stripping agents.

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CENTRIFUGE PELLET ACCELERATOR



ORNL-DWG 84M-3033 FED

Fig 1. Turbine cryoblaster concept. Pellets are fed into grooves near the center of the wheel and accelerated to 1150 ft/s as they exit the device.

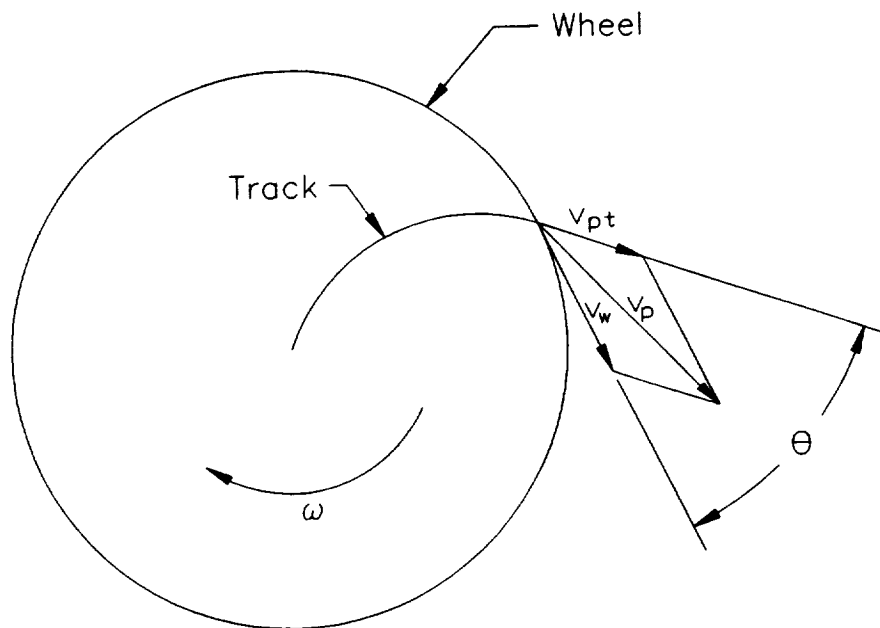


Fig 2. Wheel geometry showing vector sum of velocities as pellets exit the grooves.

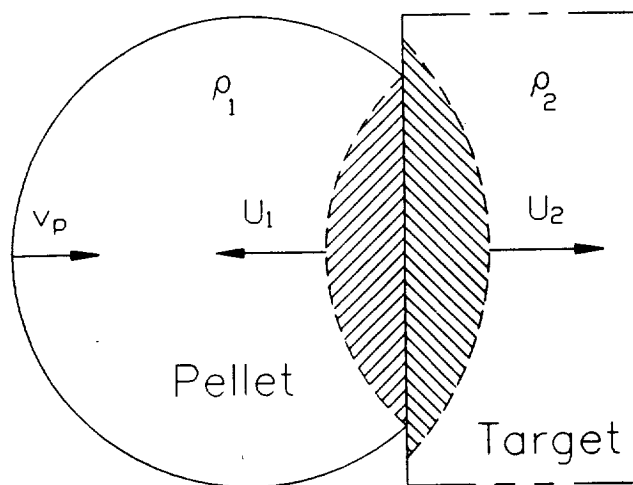


Fig 3. Shock wave propagation in pellet and surface during impact.

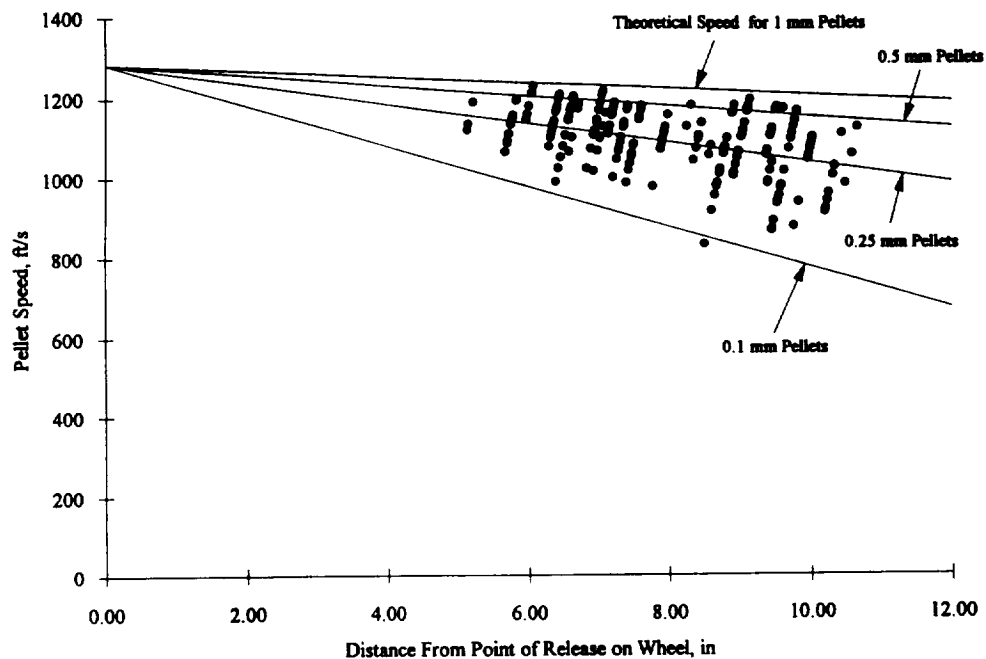


Fig 4. Measured pellet velocities with a rotor speed of 12,000 rpm. Lines show expected velocities for several size pellets undergoing aerodynamic drag.

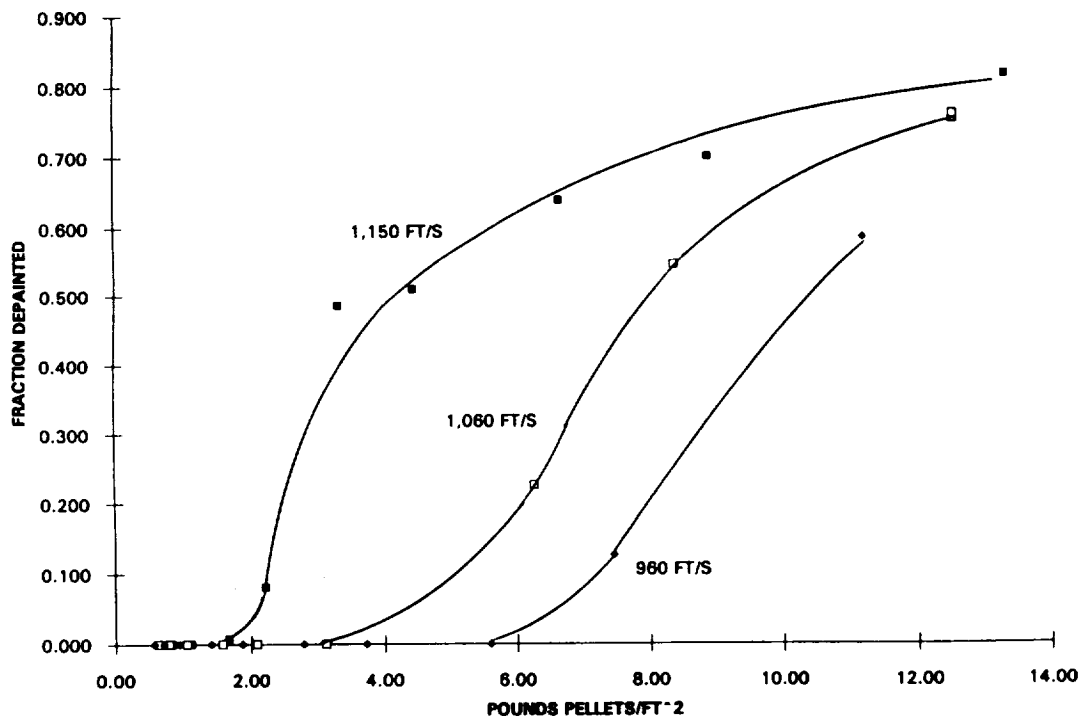


Fig 5. Fraction of surface depainted as a function of the quantity of pellets striking the surface for three different pellet speeds.

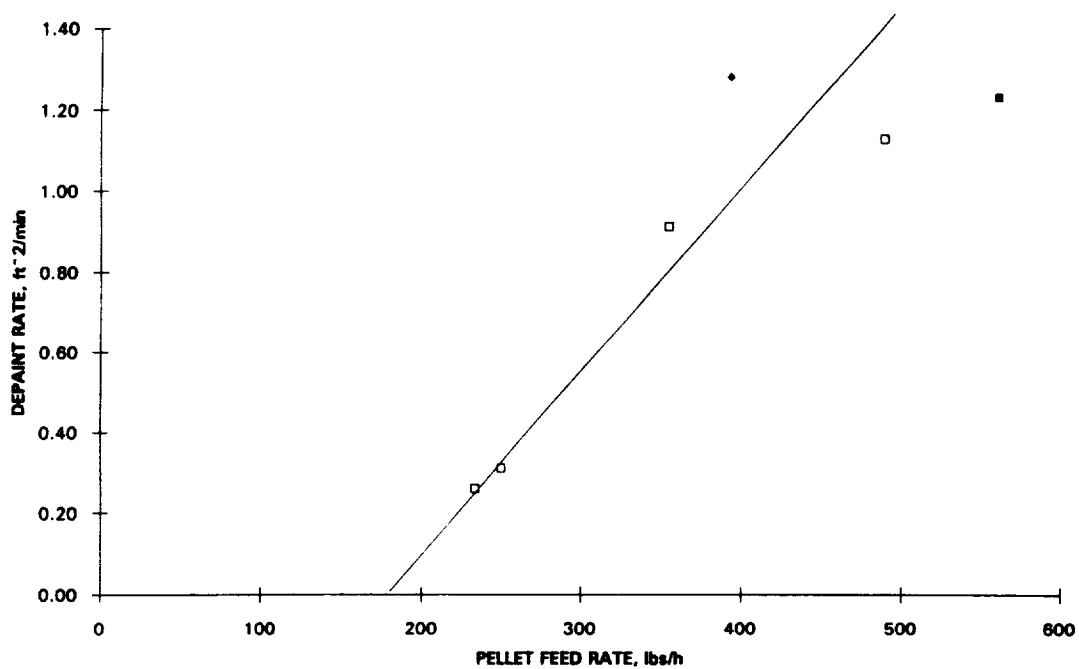


Fig 6. Optimal depaint rates as a function of pellet feed rate at 12,000 rpm (1150 ft/s).

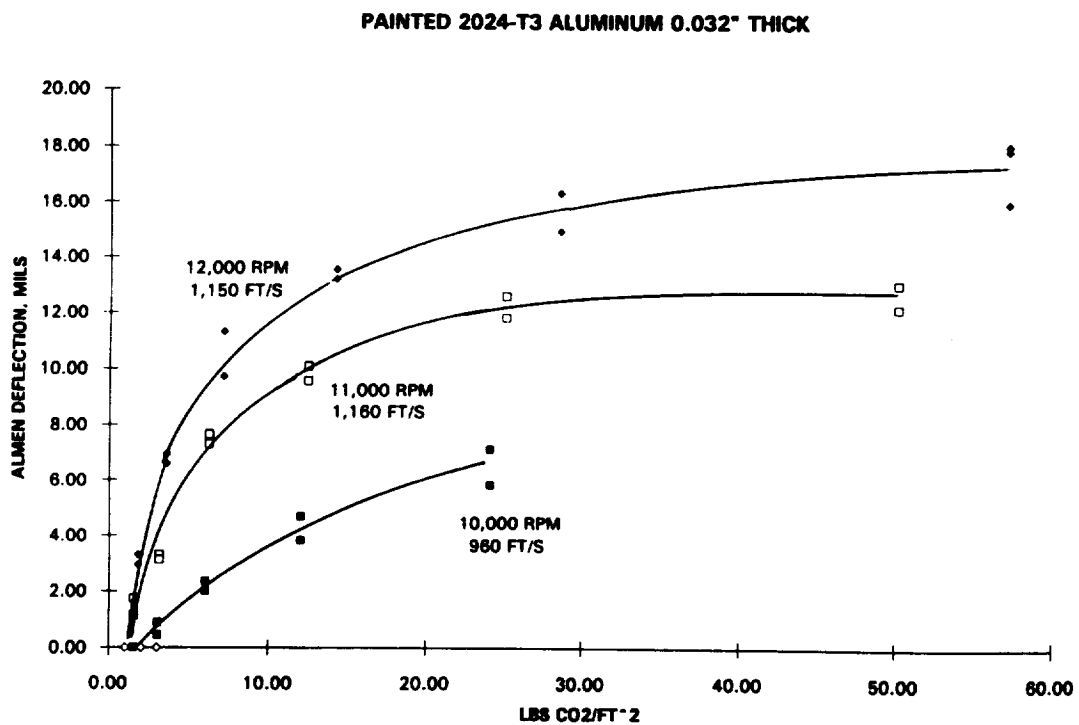


Fig 7. Almen deflection as a function of the quantity of pellets striking the surface for various speed pellets.

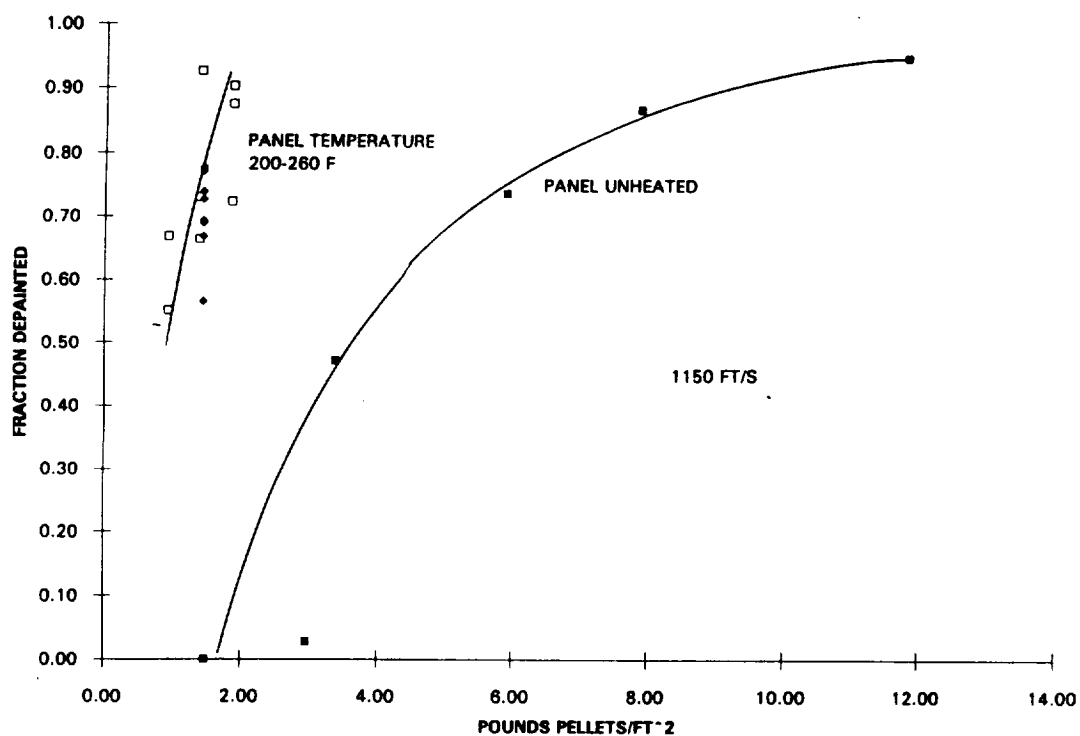


Fig 8. Fraction depainted as a function of the quantity of pellets striking the surface for heated and unheated panels using 1150 ft/s pellets.

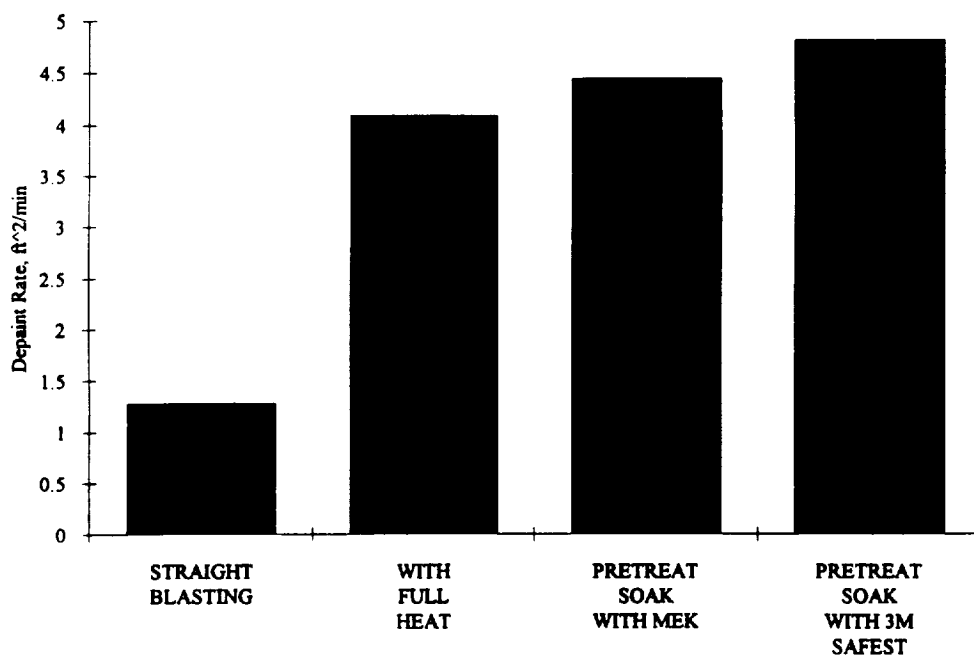


Fig 9. Depaint rates for 500 lbs/h pellets at 1150 ft/s.

